Charmed scalar resonances
— Conventional and four-quark mesons

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We propose that there coexist two scalar mesons of different structures (the conventional $^3P_0$ $\{c\bar{n}\}$ meson and a scalar four-quark $[cn][\bar{u}\bar{d}]$ meson) in the recently observed broad bumps just below the large peak of the tensor meson in the $D\pi$ mass distribution. We base this proposal on the interpretation of the $D_{s0}^+(2317)$ as a $[cn][\bar{s}\bar{n}]$ four quark meson. The strange counterparts of these scalar mesons are also studied.

We propose that the broad bumps with $\sim 240-280$ MeV widths in the $D\pi$ invariant mass distributions, seen in B decays just below the large peak of the well-known tensor meson $D_2^*(2460)$ [1, 2] should be re-interpreted as four quark mesons and conventional mesons. We do so because of the evidence that the charm-strange scalar meson $D_{s0}^+(2317)$ should be regarded as a four quark state, and we expect its non-strange partners to be in this mass region below 2460 MeV.

The charm-strange scalar meson $D_{s0}^+(2317)$ recently observed at the B-factories [3, 4, 5], was predicted [6, 7], and has been variously interpreted as the isosinglet state (the conventional scalar $\{c\bar{s}\}$ [6] which is the chiral partner of D_s^+ [7]), a scalar four-quark state [8], a DK molecule [9] or atom [10], or bound state [11], in chiral quark models [12], as a a diquark-antidiquark [13], as a mixed state of $\{c\bar{s}\}$ and a four-quark meson [14], and as an $I=1$ four quark meson [15].

The experimental result given by the CLEO collaboration [4],

$$\frac{\Gamma(D_{s0}^+ \to D_s^{*+}\gamma)}{\Gamma(D_{s0}^+ \to D_s^{*+}\pi^0)} < 0.059, \qquad (1)$$

is a severe constraint on the interpretation of the resonance, and it favours the assignment of the $D_{s0}^+(2317)$ to the $(I, I_3) = (1, 0)$ four-quark meson, $\hat{F}_I^+ \sim [cn][\bar{s}\bar{n}]_{I=1}$, $(n = u, d)$ [16]. (We use the classification of the four-quark mesons of Ref. [15].) This interpretation implies that, in addition to the conventional $\{c\bar{q}\}$ with $q = u, d, s$, scalar four-quark mesons indeed exist. If a charm-strange meson of this type exists, we would expect to find its charm-non-strange partners. Where are they?

In the $B \to D\pi\pi$ decays, the $D\pi$ invariant mass distributions shows broad bumps with $\sim 240-280$ MeV

widths just below the large peak of the $D_2^*(2460)$ tensor meson [1, 2]. We note that the results from two experiments are a little different from each other, and, in addition, it has been claimed in these papers that these bumps are consistent with the conventional scalar $D_0^* \sim \{c\bar{n}\}$, $(n = u, d)$ mesons. Given the evidence that the $D_{s0}^+(2317)$ is the $\hat{F}_I^+ \sim [cn][\bar{s}\bar{n}]_{I=1}$, $(n = u, d)$ four quark state, we regard this claim as unrealistic. There would be no room for the non-strange counterparts, $\hat{D} \sim [cn][\bar{u}\bar{d}]$, of the four-quark meson, if the above bumps were saturated only by D_0^* states. In this short note, we study decays of the D_0^* mesons and demonstrate that the conventional D_0^* and the four-quark $\hat{D}$ can coexist in the broad bump regions. We also study decays of the conventional scalar $D_{s0}^{*+} \sim \{c\bar{s}\}$ into its dominant DK decay modes. Our results will be useful in the (re)analysis of the $D\pi$ and DK invariant mass distributions we hope will occur in near future.

The conventional scalar D_0^*'s have been expected to be in the region of $m_{D_0^*} \sim 2300-2400$ MeV from various approaches: for example, potential models [17, 18], and lattice QCD [19, 20, 21]. However, the results from QCD sum rules are not yet stable — in one case [22], the result is similar to those in potential models and lattice QCD, while the result is much lower in the other case [23]. The non-strange iso-doublet counterparts, $\hat{D}$'s, of the four-quark $\hat{F}_I^+$ meson have been predicted [15] to be around $m_{\hat{D}} \simeq 2.22$ GeV (near the lower tail of the broad bumps in the $D\pi$ mass distributions), using simple quark counting with the mass difference, $\Delta_s = m_s - m_n \simeq 100$ MeV. Their widths are expected to be about 50 % broader than that of the $D_{s0}^+(2317)$ but they are still narrow [15, 24, 25]. Therefore, we expect that two different scalar iso-doublets, the conventional D_0^* and the four-quark $\hat{D}$ mesons, can co-exist in the region of the broad bump of the $D\pi$ invariant mass distributions [25, 26].

To make these arguments more precise, we first study decays of the conventional scalar D_0^* mesons. Their widths are expected to be approximately saturated by the decays to $D\pi$ states. Since the $K_0^*(1430)$'s have been

considered as $^3P_0$ $\{n\bar{s}\}$ states [27], the $D_0^* \to D\pi$ decays can be compared with the $K_0^*(1430) \to K\pi$ decays. In general the two body decay, $A(\mathbf{p}) \to B(\mathbf{p'}) + \pi(\mathbf{q})$, has the rate

$$\Gamma(A \to B + \pi) = \left(\frac{1}{2J_A + 1}\right)\left(\frac{q_c}{8\pi m_A^2}\right) \\ \times \sum_{spins} |M(A \to B + \pi)|^2, \quad (2)$$

where J_A, q_c and $M(A \to B + \pi)$ denote the spin of the parent A, the center-of-mass momentum of the final B and π mesons, and the decay amplitude, respectively. To calculate the amplitude, we use the PCAC (partially conserved axial-vector current) hypothesis and a hard pion approximation in the infinite momentum frame, i.e., $\mathbf{p} \to \infty$ [28]. In this approximation, the amplitude is evaluated at the slightly unphysical point, i.e., $m_\pi^2 \to 0$. By assuming that the q^2 dependence of the amplitude is mild, as was customary in current algebra [29], M is given by

$$M(A \to B + \pi) \simeq f_\pi^{-1}\left(m_A^2 - m_B^2\right)\langle B|A_{\bar{\pi}}|A\rangle, \quad (3)$$

where A_π is the axial charge, i.e., the counterpart of the isospin, V_π.

The *asymptotic matrix element* of A_π (or the matrix element of A_π taken between single hadron states with infinite momentum), $\langle B|A_\pi|A\rangle$, gives the dimensionless $AB\pi$ coupling strength. We parameterize the asymptotic matrix elements of A_π and A_K using asymptotic flavor $SU_f(4)$ symmetry, which is, roughly speaking, $SU_f(4)$ symmetry of asymptotic matrix elements. (Asymptotic flavor symmetry and its fruitful results were reviewed in Ref. [28].) We expect this asymptotic flavor symmetry to be broken, and a measure of the (asymptotic) flavor symmetry breaking is given by the form factor, $f_+(0)$, of the related vector current. The estimated values of $f_+(0)$'s are

$$f_+^{(\pi K)}(0) = 0.961 \pm 0.008, \quad (4)$$

$$f_+^{(\bar{K}D)}(0) = 0.74 \pm 0.03, \quad (5)$$

$$\left[f_+^{(\pi D)}(0)\right]/\left[f_+^{(\bar{K}D)}(0)\right] = 1.00 \pm 0.11 \pm 0.02, \quad (6)$$

$$= 0.99 \pm 0.08, \quad (7)$$

where the values in Eqs. (4) – (7) have been taken from Refs. [30] – [33], respectively. They imply that the asymptotic flavor $SU_f(3)$ symmetry works well while the $SU_f(4)$ is broken to the extent of 20 – 30 %. This estimate is confirmed by the observation that the asymptotic symmetry has predicted the rates [28, 34], $\Gamma(D^{*+} \to D^0\pi^+) \simeq 96$ keV and $\Gamma(D^{*+} \to D^+\pi^0) \simeq 42$ keV, which are larger by about 40 % than the observed values, $\Gamma(D^{*+} \to D^0\pi^+)_{\text{exp}} = 65 \pm 18$ keV and $\Gamma(D^{*+} \to D^+\pi^0)_{\text{exp}} = 30 \pm 8$ keV, obtained from the measured decay width [35], $\Gamma_{D^{*\pm}} = 96 \pm 4 \pm 22$ keV, and the branching fractions compiled in Ref. [36]. The above suggests that

asymptotic $SU_f(4)$ symmetry overestimates the size of the asymptotic matrix elements of the axial charge A_π between charmed meson states by about 20 % compared with the measured rate, as expected from the above values of the form factors, $f_+(0)$'s. However, for simplicity, we will use asymptotic $SU_f(4)$ symmetry relations among asymptotic matrix elements of A_π and A_K in our estimates of decay rates. When we take account for the symmetry breaking, we will note it.

We are now ready to study the $K_0^* \to K\pi$ decays and estimate the size of the asymptotic matrix element of A_π taken between $\langle K|$ and $|K_0^*\rangle$. Substituting the measured values [36], $\Gamma(K_0^* \to all) = 294 \pm 23$ MeV with $\text{Br}(K_0^* \to K\pi) = 93 \pm 10$ %, into Eq.(2) and using Eq.(3), we obtain

$$|\langle K^+|A_{\pi^+}|K_0^{*0}\rangle| \simeq 0.29, \quad (8)$$

where we have used $SU_I(2)$ isospin symmetry which is always assumed in this note.

We now use this information to estimate the decay widths of the conventional D_0^* scalar mesons. We tentatively assume $m_{D_0^*} \simeq 2.35$ GeV as the mass, which is close to the average of the experimental results in Refs. [1, 2] and is also compatible with the theoretical expectations mentioned before. The asymptotic $SU_f(4)$ symmetry relates asymptotic matrix elements of axial charges to each other [37], through relations such as

$$\langle D^+|A_{\pi^+}|D_0^{*0}\rangle = 2\langle D^0|A_{\pi^0}|D_0^{*0}\rangle \\ = \langle D^0|A_{K^-}|D_{s0}^{*+}\rangle = \langle D^+|A_{\bar{K}^0}|D_{s0}^{*+}\rangle \\ = \langle K^+|A_{\pi^+}|K_0^{*0}\rangle. \quad (9)$$

Using this equation, we compare the $D_0^* \to D\pi$ decays with the $K_0^* \to K\pi$. Insertion of Eq. (9) and the assumed mass value for D_0^* into Eq. (2) with Eq. (3) gives $\Gamma(D_0^{*+} \to D^0\pi^+) \simeq 2\Gamma(D_0^{*+} \to D^+\pi^0) \simeq \Gamma(D_0^{*0} \to D^+\pi^-) \simeq 2\Gamma(D_0^{*0} \to D^0\pi^0) \simeq 60$ MeV, where $SU_I(2)$ symmetry has been assumed. To allow for $SU_f(4)$ symmetry breaking one could reduce the above rates by $\simeq 40$ %, but even without this correction, these results suggest that the conventional scalar D_0^* mesons should be much narrower than the observed enhancements. Therefore, we do not accept that each of the measured broad bumps with a width of $\sim 240 - 280$ MeV is saturated by a single state, the D_0^* with a width of at most ~ 100 MeV. This is a compelling argument for a structure consisting of at least two resonances, one of which is the conventional scalar $D_0^* \sim \{c\bar{n}\}$ with the width $\Gamma_{D_0^*} \sim 50 - 100$ MeV located in the upper half of the enhancement. For the other we propose the scalar four-quark meson, $\hat{D}_0 \sim [cn][\bar{u}\bar{d}]$ with a narrow width, located in the lower tail of the broad bump.

Next, we study the charm-strange scalar mesons. We have noted that the experimental data on the $D_s^{*+}\gamma$ and $D_s^+\pi^0$ decays of the $D_{s0}^+(2317)$ favors its assignment to the $(I, I_3) = (1, 0)$ scalar four-quark meson, $\hat{F}_I^+ \sim [cn][\bar{s}\bar{n}]_{I=1}$, and we identified the $D_{s0}^+(2317)$ with the $\hat{F}_I^+$. This opens the question "where is the conventional

$D_{s0}^{*+} \sim \{c\bar{s}\}$ scalar meson?". Theoretical predictions of the mass of this meson are still not stable. The mass of D_{s0}^{*+} may be expected to be considerably higher than 2317 MeV, as the non-strange D_0^* are near or above this. We note the results in the literature: $m_{D_{s0}^*} \simeq 2.45 - 2.48$ GeV in potential models [17, 18], $m_{D_{s0}^*} \simeq 2.47$ GeV, in quenched relativistic lattice QCD [19], $m_{D_{s0}^*} \simeq 2.44$ GeV in unquenched ($n_f = 2$) static lattice QCD [20], and $m_{D_{s0}^*} \simeq 2.37$ GeV in relativistic unquenched lattice QCD [21], In QCDSR, the results are still more unstable. They are strongly dependent on the mass value of the charmed quark used in the calculation, i.e., for example, $m_{D_{s0}^*} \simeq 2.48$ GeV for $m_c \simeq 1.46$ GeV [22] and $m_{D_{s0}^*} \simeq 2300$ GeV for $m_c \simeq 1.13$ GeV [23]. The latter value is close to the measured mass of the $D_{s0}^+(2317)$. Although it may be tempting to use this agreement as evidence that the $D_{s0}^+(2317)$ is a conventional scalar meson, it is unsupported by the other mass estimates, and is hard to reconcile with the experimental constraint, Eq.(1), we discussed above. Since there is not yet a consensus for the predicted mass of the D_{s0}^*, we tentatively take the value $m_{D_{s0}^*} \simeq 2.45$ GeV as expected from simple quark counting with $\Delta m_s \simeq 0.1$ GeV and $m_{D_0^*} \simeq 2.35$ GeV. Our assignment of the charm-strange scalar mesons under consideration is now the conventional $D_{s0}^{*+} \sim \{c\bar{s}\}$ with a mass $m_{D_{s0}^*} \simeq 2450$ MeV and the four-quark meson $\hat{F}_I^+$ with a mass $m_{\hat{F}_I} \simeq 2317$ MeV. The width of the $D_{s0}^+(2317)$, is now constrained to be < 4.6 MeV [36]. In this note it is sufficient that it is narrow, compared to typical strong decay widths. With the assignment of the $D_{s0}^+(2317)$ to the scalar four-quark state, $\hat{F}_I^+$, such a narrow width is natural because of small overlap of the color and spin wavefunctions between the initial charmed four-quark meson and final two pseudoscalar meson states. If one assigns the observed $a_0(980)$ to the isotriplet light four-quark meson, $\hat{\delta}^s \sim [ns][\bar{n}\bar{s}]_{I=1}$, as suggested long ago in Ref. [38] and recently in Ref. [13], the observed $a_0(980) \to \eta\pi$ width of about 70 MeV, gives a width of 9 MeV for $\hat{F}_I^+ \to D_s^+\pi^0$ [16].

To estimate the width of the conventional D_{s0}^{*+} we return to Eqs.(2), (3), (8) and (9), and get

$$\Gamma(D_{s0}^{*+} \to D^0 K^+) \simeq 36 \text{ MeV}, \qquad (10)$$

where the ~ 40 % correction due to asymptotic $SU_f(4)$ symmetry breaking has not been taken into account. The decay, $D_{s0}^{*+} \to D^+ K^0$, also has the same rate because of $SU_I(2)$ symmetry, and because these two dominate the full width of the D_{s0}^{*+}, we estimate the full width to be $\Gamma_{D_{s0}^*} \sim 70$ MeV (~ 40 MeV if we allow for $SU_f(4)$ symmetry breaking). Of course, the contribution of possible isospin non-conserving $D_{s0}^{*+} \to D_s^+\pi^0$ decays will be negligibly small. Adapting the method of Ref. [16] to the mass $m_{D_{s0}^*} = 2450$ MeV estimates the width for this process as 1 keV. This is compatible with the fact that no scalar resonance has been observed in the region above the $D_{s0}^+(2317)$ resonance up to $\simeq 2.7$ GeV in the $D_s^+\pi^0$ mass distribution [3]. It should be noted that the CLEO collaboration [39] have observed a peak around 2.39 GeV in the DK mass distribution but it has been taken away as a false peak arising from the decay, $D_{s1}(2536) \to D^*K \to D[\pi^0]K$, where the π^0 has been missed. However, we hope that it might involve the true resonance corresponding to the D_{s0}^{*+} or that the resonance could be observed by experiments with higher luminosity and resolution.

To summarise, we have studied the broad enhancements in the $D\pi$ mass distributions which have been independently observed by the BELLE and FOCUS collaborations, and have pointed out that each bump is unlikely to be saturated by a single scalar $\{c\bar{n}\}$ state. We expect each enhancement to have a structure including at least two peaks, one arising from the four-quark $\hat{D} \sim [cn][\bar{u}\bar{d}]$ and the other from the conventional $D_0^* \sim \{c\bar{n}\}$, although the experimental collaborations have claimed that these bumps are consistent with the conventional scalar mesons alone. By comparing the decays of the D_0^*'s with the well-known $K_0^*(1430) \to K\pi$, the widths of the D_0^*'s predicted to be broad, $\Gamma_{D_0^*} \sim 90$ MeV (or ~ 50 MeV when the asymptotic $SU_f(4)$ symmetry breaking has been taken into account), but they are still not broad enough to comprise the whole bump. In comparison, the four-quark $\hat{D}$ mesons are expected to have widths of at most $\sim 5 - 10$ MeV.

The strange counterpart, $D_{s0}^* \sim \{c\bar{s}\}$, of the two quark scalar, D_0^*, is expected, on the basis of many different approaches, to have a mass around $m_{D_{s0}^*} \sim 2.45$ GeV. Its width is expected to be approximately saturated by the $D_{s0}^{*+} \to (DK)^+$ decays and is predicted to be ~ 70 MeV (or ~ 40 MeV when the asymptotic $SU_f(4)$ symmetry breaking has been taken into account).

We emphasise that the values of the masses and widths of the scalar resonances which have been estimated in this short note should not be taken too literally since the value of the width of the D_{s0}^+ which has been used as the input data in Ref. [15] is still somewhat uncertain, and since possible mixing between D_0^* and $\hat{D}$ through their common decay channels which may have considerable effects on the masses and widths of the mixed states [40] has been neglected. Such a mixing will depend on the details of hadron dynamics including four-quark mesons, and it will be a fruitful subject for future studies.

Finally, we point out that it is desirable that the measured broad bumps in the $D\pi$ mass distributions be (re)analyzed by using an amplitude including at least two scalar resonances. It is also expected that the charm-strange scalar, $D_{s0}^{*+} \sim {}^3P_0 \{c\bar{s}\}$, will be observed in the DK channels by experiments with high resolution and luminosity.

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